Looking beyond the average agricultural impacts in defining adaptation needs in Europe

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Abstract The effects of climate change on agriculture are often characterised by changes in the average productivity of crops; however, these indicators provide limited information regarding the risks associated with fluctuations in productivity resulting from future changes in climate variability that may also affect agriculture. In this context, this study evaluates the combined effects of the risks associated with anomalies reflected by changes in the mean crop yield and the variability of productivity in European agro-climatic regions under future climate change scenarios. The objective of this study is to evaluate adaptation needs and to identify regional effects that should be addressed with greater urgency in the light of the risks and opportunities that are identified. The results show differential effects on regional agriculture and highlight the importance of considering both regional average impacts and the variability in crop productivity in setting priorities for the adaptation and maintenance of rural incomes and agricultural insurance programmes.

Keywords Climate change · Crop yield · Yield variability · Risks · Adaptation needs

Introduction

The majority of studies on the effects of climate change on agriculture have focused on the analysis of the mean productivity of crops (Adams et al. 1998; Jones and Thornton 2003; Mougou et al. 2011; Lobell et al. 2011). However, changes in climate variability can substantially affect the inter-annual variation in agricultural productivity (Parry and Carter 1985; Semenov and Porter 1995; Chen et al. 2004). Studies of fluctuations in crop yields are scarce and rarely incorporate changes in productivity distributions resulting from climate change (Mearns et al. 1997; Rowhani et al. 2011). To overcome this deficiency, it is necessary to assess the potential risks associated with both the mean crop yield and the crop yield variability. Moreover, statistical models of productivity responses are available and are widely used to investigate the actual and future effects of climate change on crop yield as well as their temporal and spatial variation (Iglesias et al. 2000, 2012; Lobell and Burke 2010). It is possible to establish adaptation needs based on the relationship between the effects on productivity and the adaptation priorities (Iglesias et al. 2011) by understanding the combined effects of the anomalies generated by changes in the distribution functions of productivity. Therefore, establishing adaptation priorities could achieve stability in crop yield while ensuring the proper management of the risks and impacts on productivity. Such adaptations to climate change are of great importance to farmers, the food market, and policy advisers due to the large inter-annual variations that often limit on-farm productivity and the benefit of farmers (Sombroek and Gommes 1996; Porter and Semenov 2005).

The primary objective of this paper is to evaluate the role of the variability in crop productivity in addition to the average impacts on the potential risks identified in 9 agro-climatic regions covering the entire European continent. Moreover, this study emphasises the need to establish adaptation priorities based on regional disparities.

A limitation of the study is that the Mediterranean climate scenarios are derived from the rather old PRUDENCE simulations (Christensen et al. 2007) rather than from the interactive Mediterranean simulations provided by the CIRCE project (Gualdi et al. 2012); however, since agricultural adaptation in Europe is incorporated in the Common Agricultural Policy of the European Union, the value of the European-wide analysis is to compare across regions and provide information for prioritising investments in regional adaptation. The choice of using European-wide simulations of future climate allows us to define the relative importance of mean changes versus variability changes in designing and financing the adaptation strategies being consistent to previous studies.

Methods

Methodological framework

The methodological process used here integrates different components to analyse the role of variability in the risk imposed on regional crop yields under climate change scenarios and to determine adaptation priorities based on the identified needs. The analysis process is summarised in Fig. 1 and includes the link between the climate scenarios and the agro-climatic regions, the quantification of crop productivity for each year of the analysis periods, the estimation of changes in the probability distribution functions of productivity, and the definition of adaptation priorities based on the identified risks.

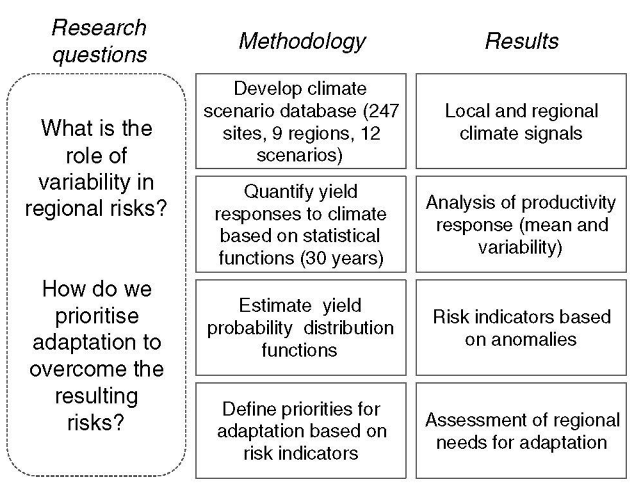


Fig. 1 Proposed framework for analysing the regional disparities in climate change impacts on European agriculture

Scenarios and regional analysis

A total of 12 simulations of the European project PRUDENCE (Christensen et al. 2007) were used. These simulations provide high-resolution climate variables in the unified coordinates CRU (Climate Research Unit) with a spatial resolution of $0.5 \times 0.5°$ (cells of approximately 50 km sides) as simulated for 8 regional climate models (RCMs) nested in the global model HadAM3H (Table 1) for the period 1961–1990 for the control scenario and for the period 2071–2100 for the climate change scenario under the emission scenarios A2 (8 simulations) and B2 (4 simulations). Monthly precipitation and temperature series were determined for each of the 30-year periods analysed for the 247 stations in the 9 agro-climatic regions defined in the study by Iglesias et al. (2012) (Fig. 2). The basic series of precipitation and temperature have been generated through the interpolation of the common CRU coordinate system. The outputs of the RCMs simulations were translated to the 247 stations using the direct interpolation method, in which the assumed value of the variable on the agricultural simulation site is the nearest element of the grid RCM (Gonzalez-Zeas et al. 2012).

Our simulations are based on the scenarios from the PRUDENCE project. The performance of the models has been evaluated through an agreed validation strategy that includes the comparison of simulated seasonal and annual means against observations as well as a comparison of observed and simulated inter-annual variability for temperature (Jacob et al. 2007). Similarly, some studies have focused on evaluating suitability of the climate models to represent the current climate, showing that some models are better than others in representing climate of the recent past (Gonzalez-Zeas et al. 2012). Nonetheless, it has also been determined that the ensemble mean performs better than individual models. Furthermore, the mean model is less prone to having large deviations in particular areas and it tends to have similar quality for most areas (Christensen et al. 2007; Jacob et al. 2007). Therefore, in order to evaluate the impact of climate change on crop yield and yield variability, we have considered all the models and also the mean values of the models.

Crop yield response to climate

Models are widely used to assess the impact of climate change on agriculture. Some of them are oriented towards regional analysis of the crop productivity (Parry et al. 2004), and others use methods that consider performance of individual crops (Ventrella et al. 2012). Both of the cases consider management at farm level; however, they use different approach to do so. In the first case, the main objective is to establish policy actions at regional level and

Table 1 Summary of the dynamic climate model-based scenarios used in this study and produced by the European PRUDENCE Project (Christensen et al. 2007)

Driving global climate models (GCM)	Centre or Institute	Regional climate models (RCMs)	Simulations		
			Control scenario CTL (1961–1990)	A2 scenario (2071–2100)	B2 scenario (2071–2100)
HadAM3H	DMI	HIRHAM	HC1	HS1	HB1
	ETH	CHRM	HC_CTL	HC_A2	
	GKSS	CLM	CTL	SA2	
	ICTP	RegCM	Ref	A2	B2
	KNMI	RACMO	HC1	HA2	
	MPI	REMO	3003	3006	
	SMHI	RCAO	HCCTL	HCA2	HCB2
	UCM	PROMES	Control	a2	b2

DMI danish meteorological institute, *ETH* Swiss federal institute of technology, *GKSS* institute of coastal research, *ICTP* physics of weather and climate section, *KNMI* the royal Netherlands meteorological institute, *MPI* Max-Planck-institute for meteorology, *SMHI* Swedish meteorological and hydrological institute, *UCM* universidad complutense de Madrid

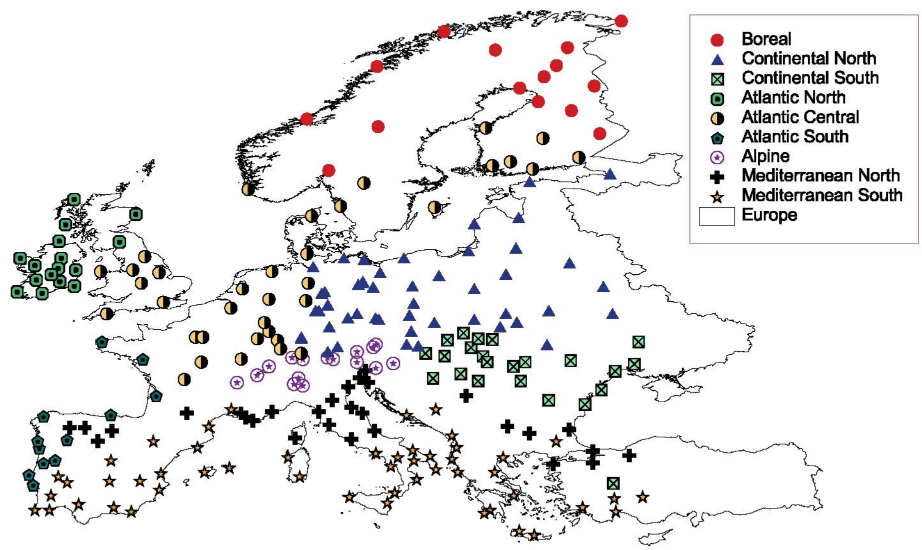


Fig. 2 Agricultural simulation sites for the 9 agro-climatic regions under the climate change scenarios (period 2071–2100)

the second case is to optimise the management of the different commodities at local level. Here, we provide an analysis to define regional adaptation needs and therefore we have selected the regional approach. This approach considers statistical models of yield response to assess the sensitivity and adaptation to climate. The yield functions have been used for analysis in Spain (Iglesias et al. 2000), China (Rosenzweig et al. 1999), and globally (Lobell et al. 2008; Lobell and Burke 2010).

Given that the policy is more focused on regions rather in crops, to determine the response of crop productivity to climate variations in the different agro-climatic regions of Europe (Fig. 2), we used the statistical models of productivity response proposed by Iglesias et al. (2012), which represent the realistic water limited and potential conditions for a mixture of crops (wheat, maize, and soybeans), the management alternatives, and the potential endogenous adaptation to climate assumed in each agro-climatic region. For each of the 247 sites in the 9 agro-climatic regions, the yield response for the 30-year intervals within the control and climate change (A2 and B2) scenarios were quantified.

The statistical models of productivity response used here are specified according to the following relationship:

$$Y_i = \alpha^1 + \alpha^2(CO_{2i}) + \sum_{j=1}^{12} \alpha_j^3(T_{ji}) + \alpha^4(T_{ai}) + \sum_{j=1}^{12} \alpha_j^5(PP_{ji}) + \alpha^6(PP_{ai}) + u_i, \quad (1)$$

where Y_i is the crop yield (kg ha^{-1}), T_{ji} is the temperature of the months 1–12 of the growing period (which varies with the location and crop, see Table 2), PP_{ji} is the total

Table 2 Months during which the climate explains a higher proportion of crop productivity variation in the agro-climatic regions

Agro-climatic regions	Validation site	Months which climate explains a higher proportion of crop productivity variation
Boreal	Oslo	June–September and annual average
Continental North	Muenchen	May–August and annual average
Continental South	Bucharesti	April–July and annual average
Atlantic North	Cork	May–August and annual average
Atlantic Central	Dijon	April–July and annual average
Atlantic South	Lisboa	March–June and annual average
Alpine	Insbruck	June–September and annual average
Mediterranean North	Pescara	March–June and annual average
Mediterranean South	Almeria	March–June and annual average

amount of water (precipitation plus irrigation) received by the crop (mm), i refers to the year, j is the month, a refers to the annual values, 1–6 are parameters, and u is the random term that allows for the residues.

The estimated coefficients and the standard deviations of the parameters of the statistical models of productivity response involving two monthly values of temperature and precipitation are summarised in Table 3. These functions were derived from the process-based crop responses to management and climate by using DSSAT crop models for wheat, maize, and soybeans (Jones et al. 2003; Rosenzweig and Iglesias 1998). The selected crops have been used in several studies to characterise world food production (Hammer et al. 2005; Challinor et al. 2005) and are representative of roughly two-thirds of arable land in most regions. The statistical functions of yield response have been calibrated and validated in the 9 agro-climatic regions (Ciscar et al. 2011; Iglesias et al. 2012) and then implemented in the 247 agricultural sites to provide a spatial analysis of crop yield response to climate change.

This approach overcomes the limitation of data requirements for process-based crop models using statistical functions in order to expand process-based crop models results over large areas. The methodology takes into account the impact on the mean values of productivity and also the potential risk associated with the inter-annual variability of productivity given by the coefficient of variation.

The relative changes in crop productivity as a consequence of climate change have been calculated as follows:

$$\Delta Y = \frac{Y_{CC} - Y_{CTL}}{Y_{CTL}} \times 100, \quad (2)$$

where ΔY is the variation in the crop yield (difference between crop yield under climate change scenario (Y_{CC}) and crop yield under control scenario (Y_{CTL}), in percent).

The variation in the variability of the crop productivity has been obtained by calculating the changes in the coefficient of variation of productivity during the 30 years analysed, as follows:

$$\Delta Cv = \frac{Cv_{CC} - Cv_{CTL}}{Cv_{CTL}} \times 100, \quad (3)$$

where ΔCv is the change in the coefficient of variation of crop yield (difference between coefficient of variation of crop yield under climate change scenario (Cv_{CC}) and the coefficient of variation of crop yield under control scenario (Cv_{CTL}), in percent).

In addition, this study introduces the risk analysis using indicators based on anomalies given by the changes in the probability distribution functions of the crop yield under climate change scenarios with respect to the control scenario.

Yield probability distributions functions

Climate change is expected to affect both the mean values of crop productivity and its variability (Torriani et al. 2007). Considering that these changes in crop yield could be substantial, it is possible to represent the mean and inter-annual behaviour using probability distribution functions that represent the behaviour of annual productivity. According to the changes occurring in the form of distributions, we can determine the anomalies that are generated under future scenarios with respect to the control scenario. Thus, this study considers four possible cases that take into account the changes in the average yield and the variability of productivity (Fig. 3).

The first case occurs when the productivity changes move the entire distribution to a lower value of productivity and greater variability (Fig. 3a). In the second case, the productivity changes move the entire distribution to a higher productivity and greater variability (Fig. 3b). The third case is characterised by the distribution shifting the mean towards a lower value of productivity and less variability (Fig. 3c). Finally, in the last case, the distribution change shifts the mean towards higher productivity and less variability (Fig. 3d). The detected anomalies given by the changes in the distribution functions of productivity

Table 3 Estimated coefficients of the statistical model of productivity response (Eq. 1) (Iglesias et al. 2012)

	Boreal	Continental north	Continental south	Atlantic north	Atlantic central	Atlantic south	Alpine	Mediterranean north	Mediterranean south
T_4			0.1831						
			(0.0000)						
T_5		0.4759	0.0050			−0.0059		−0.2298	
		(0.0018)	(0.0000)			(0.0000)		(0.0003)	
T_6	0.0429	0.0050	−0.0571		0.1107		0.0193		
	(0.0017)	(0.0113)	(0.0045)		(0.0069)		(0.0462)		
T_7		−0.2731		−0.0056			0.0564	−0.0127	−0.0313
		(0.0038)		(0.0000)			(0.0357)	(0.0008)	(0.0004)
T_8	0.2010	−0.1571							
	(0.0001)	(0.0009)							
T_a	0.0769	0.1572		0.2752	0.5105	−0.2014	0.3401		
	(0.0001)	(0.0009)		(0.0384)	(0.0173)	(0.0000)	(0.0081)		
PP_4						0.0173		0.0157	0.0013
						(0.0015)		(0.0091)	(0.0005)
PP_5			0.0153					0.0056	
			(0.0115)					(0.0339)	
PP_6			0.0172	0.0153		0.0422			
			(0.0200)	(0.0013)		(0.0401)			
PP_7					0.1067				
					(0.0375)				
PP_8		0.0041		0.0102					
		(0.0257)		(0.0014)					
PP_9	0.0182								
	(0.0279)								
PP_a	0.0055	0.0015	0.0102	0.0136	0.0298		0.0077		0.0112
	(0.0032)	(0.0265)	(0.0138)	(0.0104)	(0.0264)		(0.0001)		(0.0000)
R^2	0.62	0.71	0.83	0.72	0.60	0.69	0.67	0.89	0.78

Standard deviation is shown in parenthesis. T_4 to T_8 correspond to temperature in months 4–8, T_a refers to the annual temperature, PP_4 to PP_9 correspond to crop water (precipitation plus irrigation) in months 4 to 9, and PP_a refers to the annual crop water. R^2 is the coefficient of determination

determine the level of impact and the risk on crop productivity under future climate change scenarios. These predicted effects and risks are used as the basis for adaptation needs based on the degree of vulnerability that characterises the different agro-climatic regions.

Definition of the priorities for adaptation

Agriculture is one of the economic sectors most likely to be strongly affected by climate change (Hertel et al. 2010). For this reason, adaptation is a key factor that will establish the future severity of climate change impacts on food production and agriculture (Smit et al. 2000; Schmidhuber and Tubiello 2007; Lobell et al. 2008; Meinke et al. 2009; Lee 2009). Thus, the link between the vulnerability of crop yield given by the anomalies generated by the climate scenarios and the adaptation needs relative to the projected impacts and risks could facilitate a better understanding of the potential implications of climate change and the adaptation priorities at the regional level. Considering the combined effects of changes in the mean and overall variability in regional productivity, it is possible to prioritise the agro-climatic regions where the impacts must be addressed with greater urgency in the light of the identified risks and opportunities. Here, four cases (Fig. 4) are identified to determine the adaptation priorities. For example, an increase in the mean yield and a decrease in yield variability create a favourable condition, thereby allowing for the identification of adaptation needs and the elimination of barriers to potential opportunities. Conversely, a decrease in the mean yield and an increase in yield variability correspond to an unfavourable situation,

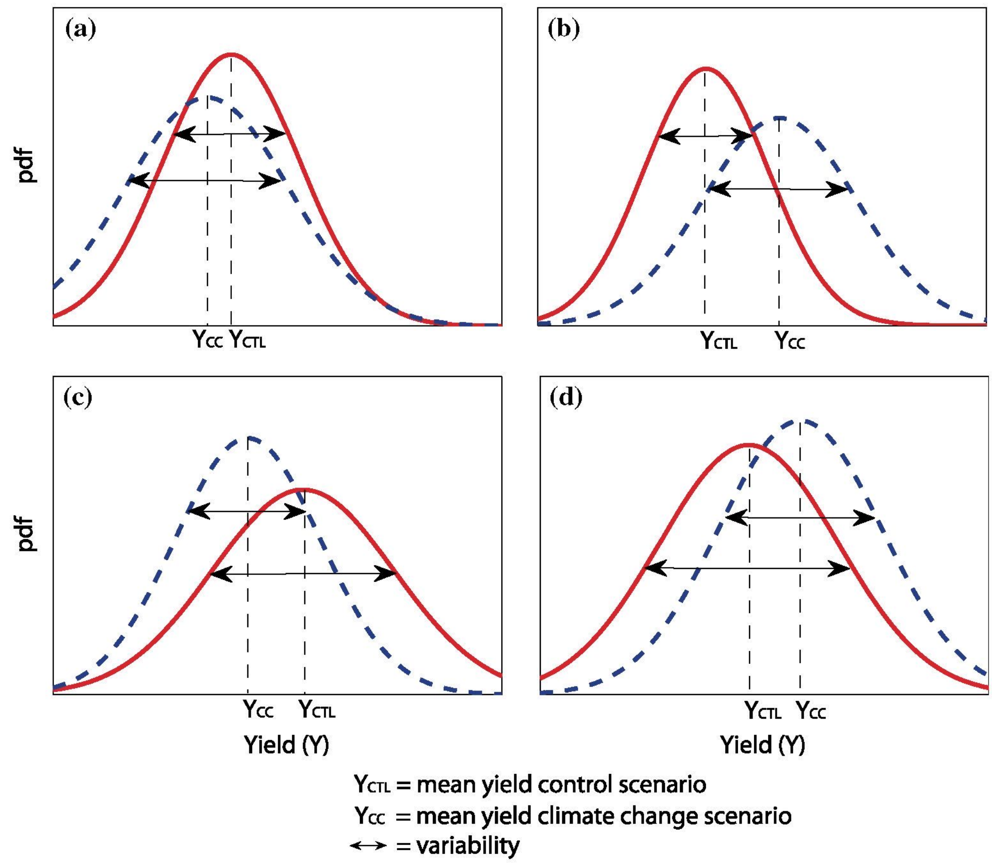


Fig. 3 Probability distribution functions (pdfs) of the crop yield under the climate change scenario (*dashed*) and control scenario (*solid*). The *vertical lines* indicate the means, and the *double-headed arrows* indicate the variance: **a** lower productivity and greater variability, **b** greater productivity and variability, **c** lower productivity and variability, and **d** greater productivity and lower variability

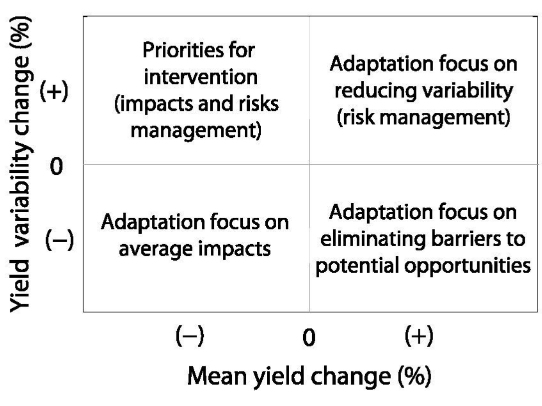


Fig. 4 Prioritising the adaptation requirements as a result of the combined effects of the changes in the mean yield and the yield variability

thereby indicating the priorities for intervention that include the management of impacts on crop yield as well as the management of risks. In addition, an increase in both the mean yield and the yield variability requires adaptations that emphasise a reduction in the variability, whereas a decrease in both the average yield and the yield variability requires adaptations that focus on the average impacts.

Results

Local and regional climate signals

The projected annual mean changes in temperature and precipitation obtained from the 12 simulations under the emissions scenarios A2 and B2 for the period 2071–2100 relative to the period 1961–1990 are summarised in Fig. 5, which shows the average behaviour in each of the 9 agro-climatic regions. In all simulations of the RCMs and for all agro-climatic regions, there is an increase in temperature ranging from 1.1 to 4.7 °C. This increase in temperature is greater in scenario A2 than in scenario B2. In the case of precipitation, the behaviour varies between the agro-climatic regions, and the simulation results show both increased and decreased precipitation with changes ranging between −20 and 20 %. The results presented in Fig. 5 show the average change in the future scenario (period

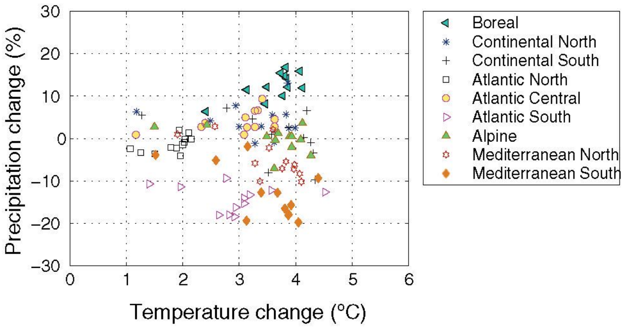


Fig. 5 Changes in annual average temperatures and total annual precipitation in 2071–2100 relative to 1961–1990 averaged over each agro-climatic region from 12 simulations under the A2 and B2 scenarios

2071–2100) with respect to the control scenario (period 1961–1990).

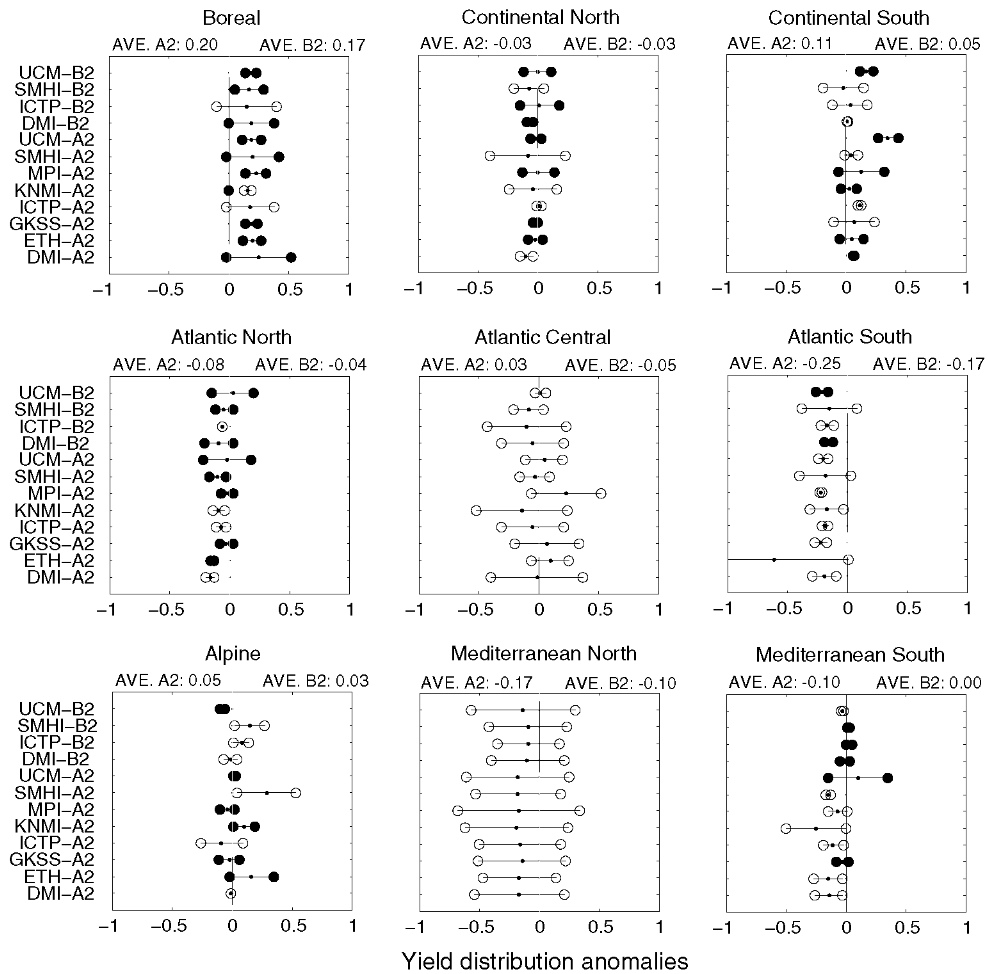
Analysis of productivity responses

The relative changes in the mean crop yield and the yield variability in the agro-climatic regions were calculated for the two climate change scenarios, and the results are presented in Table 4. As an average of each emission scenario for the regional climate model values, the results indicate that the projected climate change is expected to increase crop yields in the Boreal, Continental South, Alpine, and Atlantic Central regions, under the A2 and B2 emission scenarios. However, the mean crop yield shows a decrease in response to the projected climate change scenarios in the Atlantic South, Mediterranean North, Mediterranean South, Atlantic North, and Continental North regions, under the A2 and B2 scenarios. The climate change scenarios also exert a considerable influence on the variability in crop yields (Table 4; value in parentheses). The variability increases under the A2 scenario, especially in the Mediterranean North, Atlantic Central, Atlantic South, Mediterranean South, and Continental North regions. Under the B2 scenario, the variability in the crop yield increases in the Mediterranean North, Atlantic Central, Continental South, Alpine, and Atlantic South. In the remaining regions, the crop yield variability decreases slightly in the Boreal, Continental South, and Atlantic North regions under the A2 scenarios, and the yield variability is predicted to decline in the Boreal, Continental North, Atlantic North, and Mediterranean South agro-climatic regions under the B2 scenarios. It is important to note that in some regions; especially the Mediterranean North and Atlantic Central, the changes in variability of crop yield are much larger than the changes in crop productivity. The mean yield and the yield variability experience a greater extent of change under the A2 scenario relative to the B2 scenario.

Table 4 Average regional changes in the crop yield and yield variability (numbers in parentheses) under the A2 and B2 scenarios for the period 2071–2100 compared to the control scenario for the period 1961–1990

Agro-climatic regions	A2 scenario yield change (%)									B2 scenario yield change (%)				
	DMI1	ETH	GKSS	ICTP	KNMI	MPI	SMHI	UCM	Mean A2	DMI	ICTP	SMHI	UCM	Mean B2
Boreal	25	20	19	18	16	23	20	19	20	15	13	14	16	14
	(−27)	(−7)	(−5)	(20)	(3)	(−8)	(−22)	(−8)	(−7)	(−19)	(25)	(−12)	(−4)	(−2)
Continental North	−10	−2	−2	1	−4	0	−8	−2	−3	−7	1	−8	0	−4
	(5)	(−6)	(−2)	(2)	(20)	(−14)	(32)	(−5)	(4)	(−2)	(−16)	(12)	(−12)	(−4)
Continental South	7	5	7	12	3	13	4	35	11	1	3	−2	13	4
	(−1)	(−10)	(17)	(2)	(−6)	(−19)	(6)	(−9)	(−3)	(0)	(14)	(17)	(−5)	(7)
Atlantic North	−16	−15	−3	−7	−9	−2	−10	−2	−8	−11	−7	−5	3	−5
	(4)	(−1)	(−6)	(4)	(5)	(−5)	(−7)	(−20)	(−3)	(−12)	(0)	(−8)	(−18)	(−9)
Atlantic Central	−1	10	7	−5	−14	23	−3	5	3	−5	−11	−8	1	−6
	(38)	(15)	(27)	(26)	(38)	(29)	(12)	(15)	(25)	(26)	(33)	(13)	(4)	(19)
Atlantic South	−19	−61	−22	−18	−17	−22	−18	−20	−25	−20	−20	−19	−26	−21
	(10)	(62)	(5)	(2)	(14)	(1)	(21)	(4)	(15)	(−3)	(6)	(23)	(−5)	(5)
Alpine	−1	16	−2	−9	10	−4	29	2	5	−1	8	11	−8	3
	(0)	(−19)	(−8)	(18)	(−9)	(−6)	(24)	(−1)	(0)	(6)	(7)	(12)	(−2)	(6)
Mediterranean North	−17	−17	−14	−16	−19	−17	−18	−18	−17	−12	−11	−11	−17	−13
	(37)	(31)	(36)	(34)	(43)	(51)	(35)	(43)	(39)	(30)	(26)	(32)	(44)	(33)
Mediterranean South	−14	−15	−3	−11	−25	−7	−15	10	−10	−1	3	3	−3	0
	(12)	(12)	(−5)	(8)	(25)	(8)	(2)	(−25)	(5)	(−4)	(−2)	(−1)	(1)	(−2)

Fig. 6 Range of anomalies in the yield distribution functions under climate change conditions (scenarios A2 and B2) with respect to the control for the 9 agro-climatic regions. The change in the mean value is represented by the displacement of the *middle point* in the range of anomalies. The change in coefficient of variation is represented by the width of the range of *anomalies*; *black circles* indicate decreased variability, and *white circles* indicate increased variability. AVE. A2 and AVE. B2 refer to the mean values of the models



Risk indicators based on anomalies

Figure 6 shows the indicators of the impacts and risks identified in the different agro-climatic regions of Europe based on the detected anomalies in crop yields as projected in the 12 climate change simulations.

These indicators highlight the vulnerability of a region to the projected impacts and allow us to assess the magnitude of changes in both the mean values and the variability of these impacts. The indicators also demonstrate the extent to which the impact differs at the spatial scale. Considering that climate variability affects the productivity variability, the changes in behaviours within the different agro-climatic regions as well as between the different simulations are highlighted. Based on the behaviour of all simulations for the A2 emissions scenario, the mean crop yields show positive changes in the Boreal, Continental South, Atlantic Central, and Alpine regions. Similar results are observed for scenario B2, with the exception of the Atlantic Central and Mediterranean South regions that show a respective decrease and increase in the mean yields. In contrast, the Continental North, Atlantic North, Atlantic South, Mediterranean North, and Mediterranean South regions show decreases in the changes of mean crop yields for scenarios A2 and B2. With respect to the variability, the anomalies show a clear increase in risk in the Atlantic Central and Mediterranean North regions for scenarios A2 and B2; a relatively small increase in variability is observed in the Atlantic South and Mediterranean South regions under the A2 scenario. The remaining agro-climatic regions are characterised by a decrease in the variability of productivity. Nonetheless, certain discrepancies between the different simulations are observed.

Assessment of regional needs for adaptation

The magnitude of the risk indicators for crop productivity reflects the importance of the changes in the mean and variability as an individual level; however, adaptation needs are directly associated with the joint behaviour of the anomalies in both the mean values and the yield variability. Figure 7 shows the combined effect of these two indicators

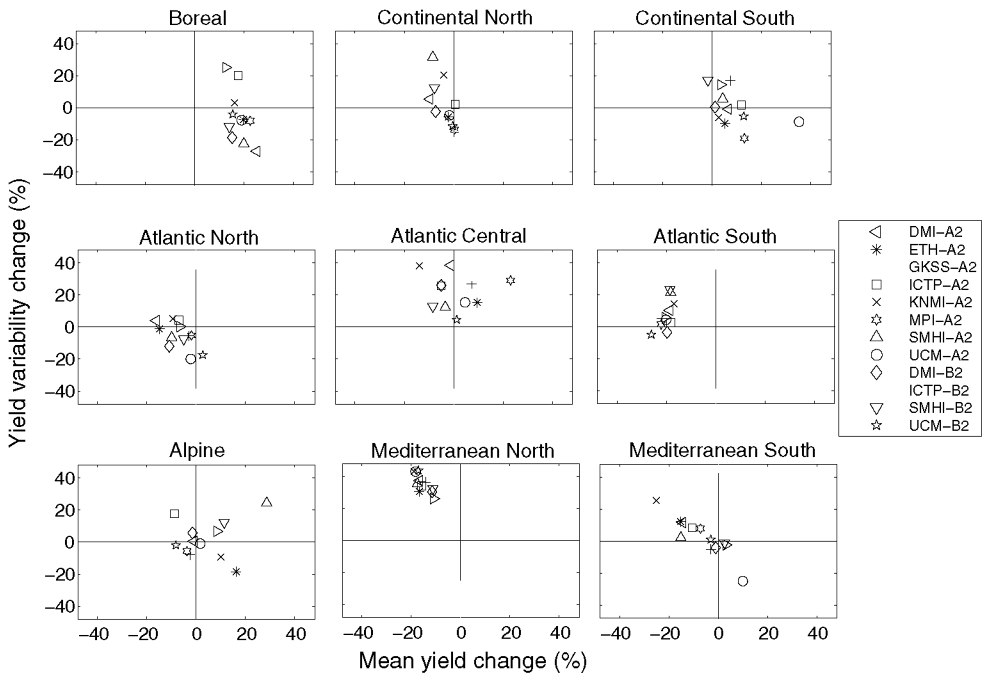


Fig. 7 Outcome of regional disparities for the combined effect of the changes in mean crop yield and variability in crop yield for the period 2071–2100 (from 12 A2 and B2 scenario simulations) with respect to 1961–1990 (CTL scenario) for the 9 agro-climatic regions

Table 5 Examples of adaptation strategies addressing changes in mean yield and yield variability in the different agro-climatic regions of Europe

Adaptation needs	Example of potential adaptation measures
Adaptation focused on average impacts	Change crops and cropping patterns
	Change cultivation practices
	Increase input of agro-chemicals
	Introduce new irrigation areas
	Develop climate change resilient crops
	Diversify livelihood
	Relocate farm processing industry
Adaptation focused on reducing variability	Promote insurance
	Provide supplemental irrigation
	Shift crops from vulnerable areas
	Improve soil moisture retention capacity
Adaptation focused on both changes in the mean and the variability	Implement regional adaptation plans
	Provide advisory services
	Promote research on technology and biotechnology
	Promote research on water use efficiency
	Promote research on management and planning
Adaptation focused on eliminating barriers to potential impacts	Develop adaptation plans to maintain optimal farming conditions and increased crop productivity
	Provide advice based on expert judgment

for the 12 climate change simulations; these effects are used to establish priorities for adaptation based on the needs identified in each of the agro-climatic regions in Europe. According to Fig. 7, the average behaviour under the climate scenarios shows that crop productivity in the Boreal region is characterised by a situation that is favourable to climate change. Therefore, adaptation requirements in this region should focus on eliminating the barriers to potential agriculture opportunities. In contrast, the indicators show an unfavourable change in crop productivity in the Atlantic Central, Atlantic South, Mediterranean North, and Mediterranean South regions. In these cases, the adaptation priorities should focus on both the management of the average impacts and the management of risk associated with these effects. The Continental North region shows a variable performance between the different scenarios. The risk indicators of that region are considered unfavourable for some simulations, thereby indicating a need for adaptation priorities that address both the mean yield and the yield variability; however, for other simulations, this area needs to prioritise only the impacts on the mean values of productivity. The Alpine region shows disparate results under the different scenarios, although the need for adaptation measures to address the average effects and the impacts of variability is emphasised. The need for adaptation measures that focus on the mean productivity is indicated for the Atlantic North region. Finally, in the Continental South region, favourable results are indicated for certain scenarios, whereas other results emphasise the need for adaptation measures with an emphasis on the variability.

According to the adaptation needs identified in each of the agro-climatic regions in Europe, potential adaptation measures are summarised in Table 5, in order to address the four cases that involve adaptation priorities.

Discussion and conclusions

This evaluation of the combined effect of the changes in the mean productivity and the variability of crop yields show that these indicators provide a clearer and more complete perspective for assessing regional adaptation needs. The risk indicators based on the anomalies show a differential effect on agriculture, thereby highlighting the disparities between the different agro-climatic regions. Similar results were obtained by Rabbinge and van Diepen (2000), Olesen et al. (2007), and Ciscar et al. (2011). Thus, the impact of climate change will have a beneficial effect on the Boreal region, with increases in the mean yield and decreases in the variability in productivity. In contrast, in the Atlantic Central, Atlantic South, Mediterranean North, and Mediterranean South regions, adaptation priorities should focus on better management centred on increasing the mean crop productivity and reducing the variability. The Alpine and Continental North regions show a greater discrepancy between the different simulations than the other regions. Certain variances observed indicate the importance of the need to prioritise the mean impacts and the variability of productivity, whereas other predictions indicate the need to prioritise based only on the mean impacts. In the Atlantic North region, there is a need to prioritise the mean impacts, and in the Continental South region, it is important to prioritise the risk by focusing on reducing the productivity variability. Results obtained by Ciscar et al. (2011) and Iglesias et al. (2012) emphasise crop productivity increases in northern Europe and decreases in southern Europe, similar to our results. However, yet European scale impact assessments are full of difficulties for understanding the regional importance of variability and change in future agricultural production, and the role of future regional variability has only been poorly explored. The specification of policy instruments addressing changes in the average crop productivity (e.g., structural measures) may be very different to those addressing the risk from increased yield variability (e.g., insurance). In consequence, if climate change impacts on variability are not considered, it may lead to inappropriate adaptation strategies. As an example, the Mediterranean North region shows greater changes in variability than in the mean crop yield, meaning necessary adaptation measures should focus especially on reducing variability (e.g., supplemental irrigation). Based on these results, productivity variability will clearly be a key factor when determining the future goals of agricultural policies, the maintenance of rural incomes, and agricultural insurance programs. This conclusion is supported by the studies of Porter and Semenov (2005), Isik and Devadoss (2006), which indicate that increases in the temporal and spatial variability of productivity correspond with less security in the quantity and quality of the food supply.

Based on this study, it can be concluded that if climate change projections prove to be accurate, the variability in productivity could be detrimental in certain agro-climatic regions if the institutions, farmers, and stakeholders are not prepared to address the aggregate effect of variability, to the average impacts on agriculture by incorporating adaptation measures for risk management.

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